Janet Conrad, MIT
WINP2015, 2/5/15

ν_μ Disappearance

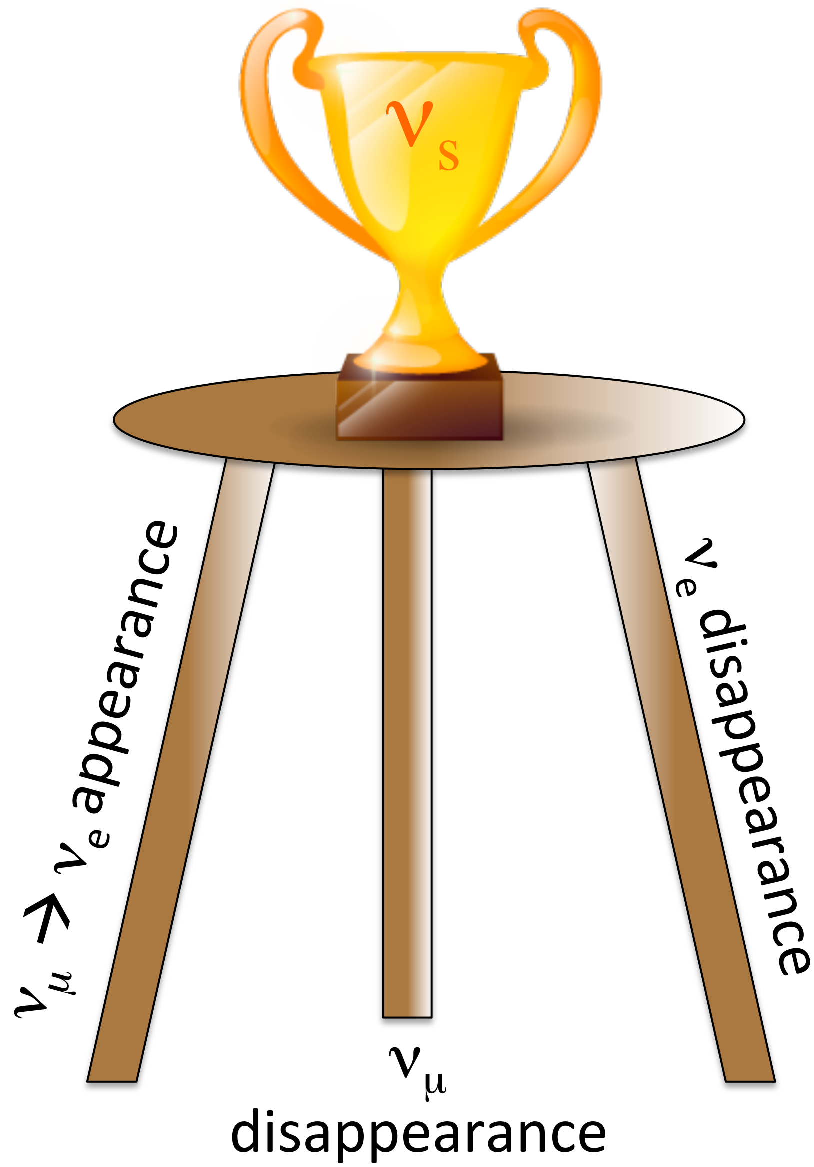
"Let's talk about it!"

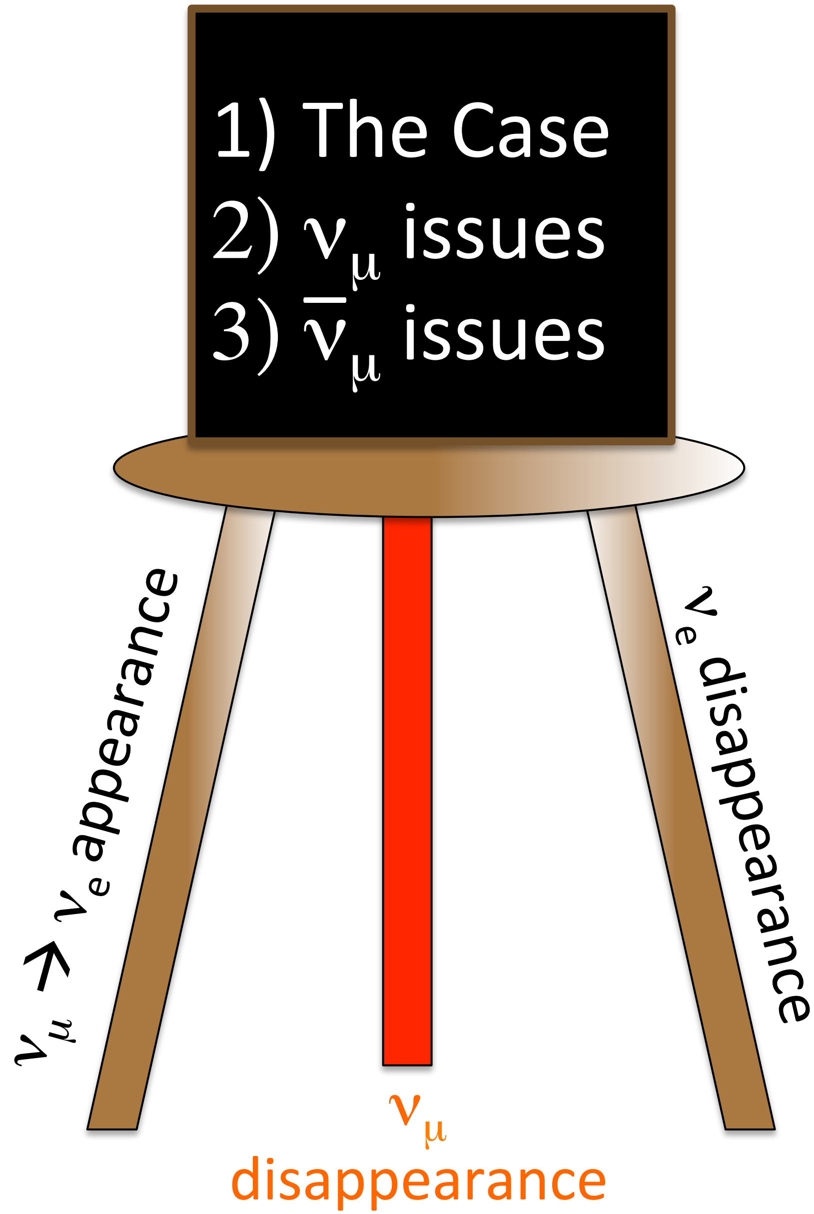
The long-term future of particle physics in the US is largely neutrino-based.

...You get to the long-term future via the intermediate-term future!

An intermediate neutrino program that is <u>scientifically decisive</u> is the best path to long-term-future success for DOE and NSF.

Success for sterile neutrinos studies sits on a "3-legged table"…





1) The Case
2) ν_μ issues
3) $\bar{\nu}_\mu$ issues
$\nu_\mu \rightarrow \nu_e$ appearance
ν_μ disappearance
ν_e disappearance

The Case for Near-Future μ-flavor Disappearance Experiments

There are “signals” in $\nu_\mu \rightarrow \nu_e$ appearance and ν_e disappearance,

No signal in ν_μ disappearance yet!
…And there is “tension”

Why?

1. The observed signals are due to standard model processes, not sterile neutrinos

2. There are issues with some of the observed signals, but not others,
   leading to the wrong global fit.

3. The tension has to do with background, not signal, and
   ν_μ disappearance is right around the corner.

4. The tension has to do with more complicated physics than we are
   putting into our models.

1. What if all of the existing anomalies are Standard Model?

Given this as a scenario, should we not just wait on nm disappearance
Until we have more data from in $\nu_\mu \rightarrow \nu_e$ appearance and ν_e disappearance?

I don't think so…

There are now many viable models that include steriles.

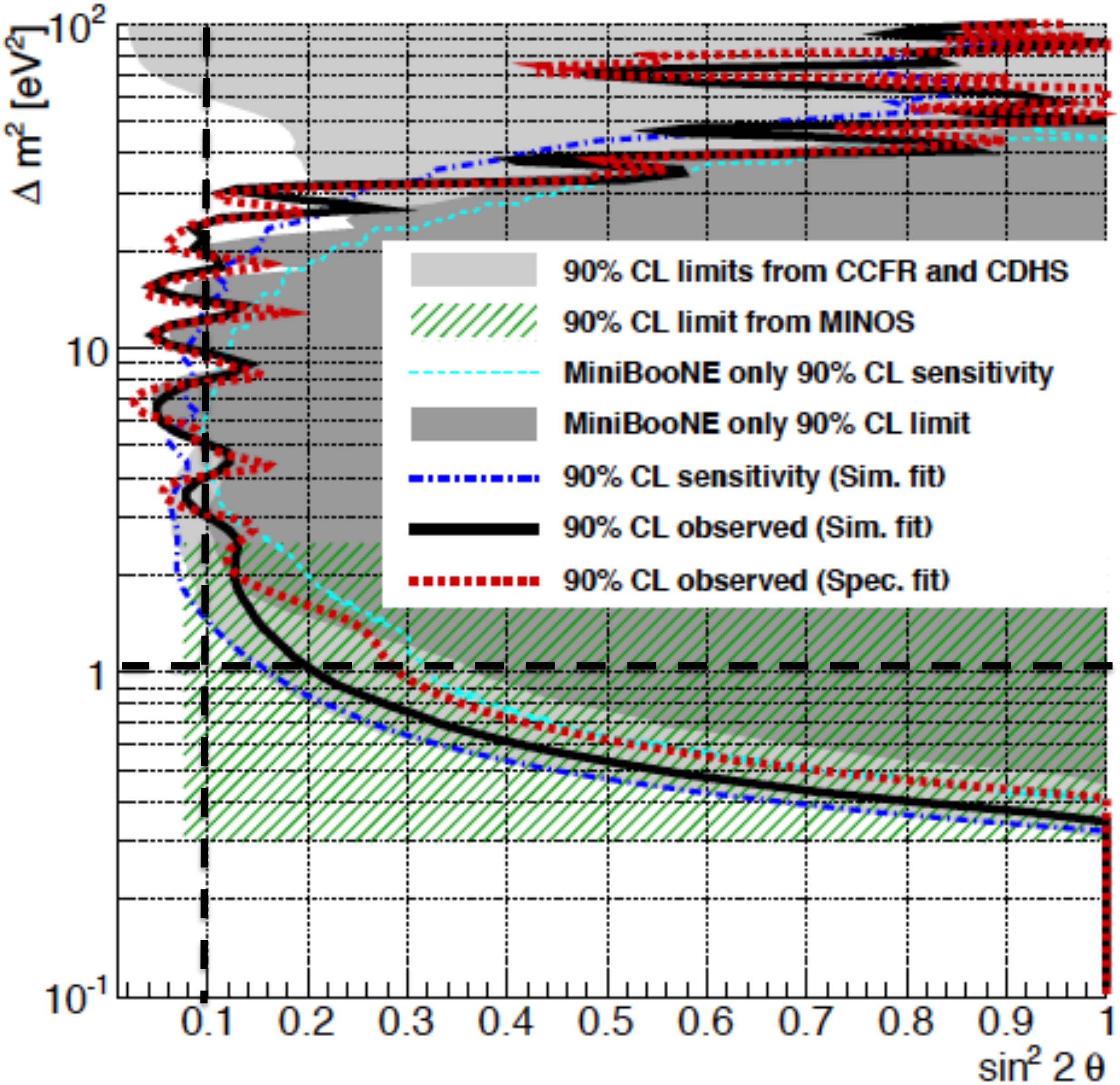
→ If we have not found them already, they still have a chance of being out there.
Probably as good of a chance as supersymmetry or axions.
We should be looking for them.

We should move forward with ν_μ disappearance experiments
regardless of what happens with the present anomalies.

In this event, we want the experiments to substantially increase the explored space past the present point where present data sits.

Existing experiments have rather similar limits!

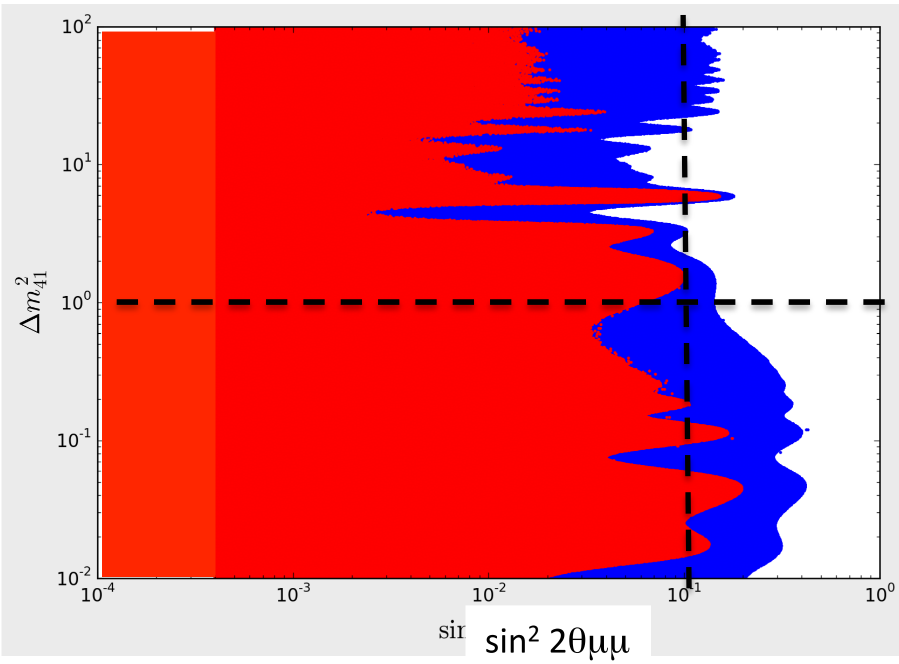
We need substantial coverage Well below $\sin^2 2\theta=0.1$



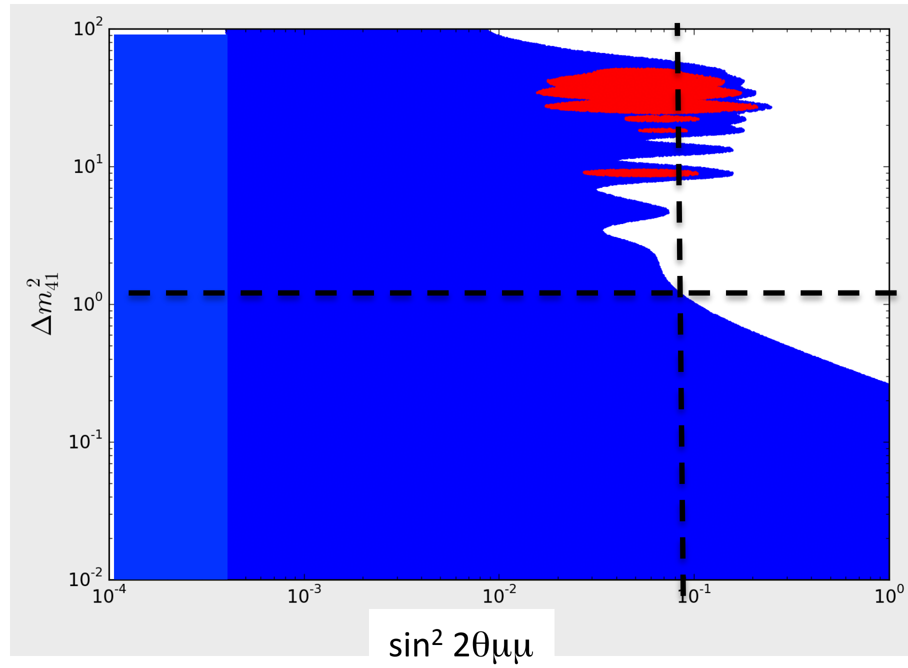
arXiv:1106.5685

Putting all μ-flavor disappearance data sets together, but separating the running modes…

$\bar{\nu}$



ν



99% CL , 90% CL

A mix of the experiments, especially CDHS+Sci/MiniBooNE, gives an allowed “island” but at <2σ

Both modes need new experiments
To give a substantial push below $\sin^2 2\theta=0.1$

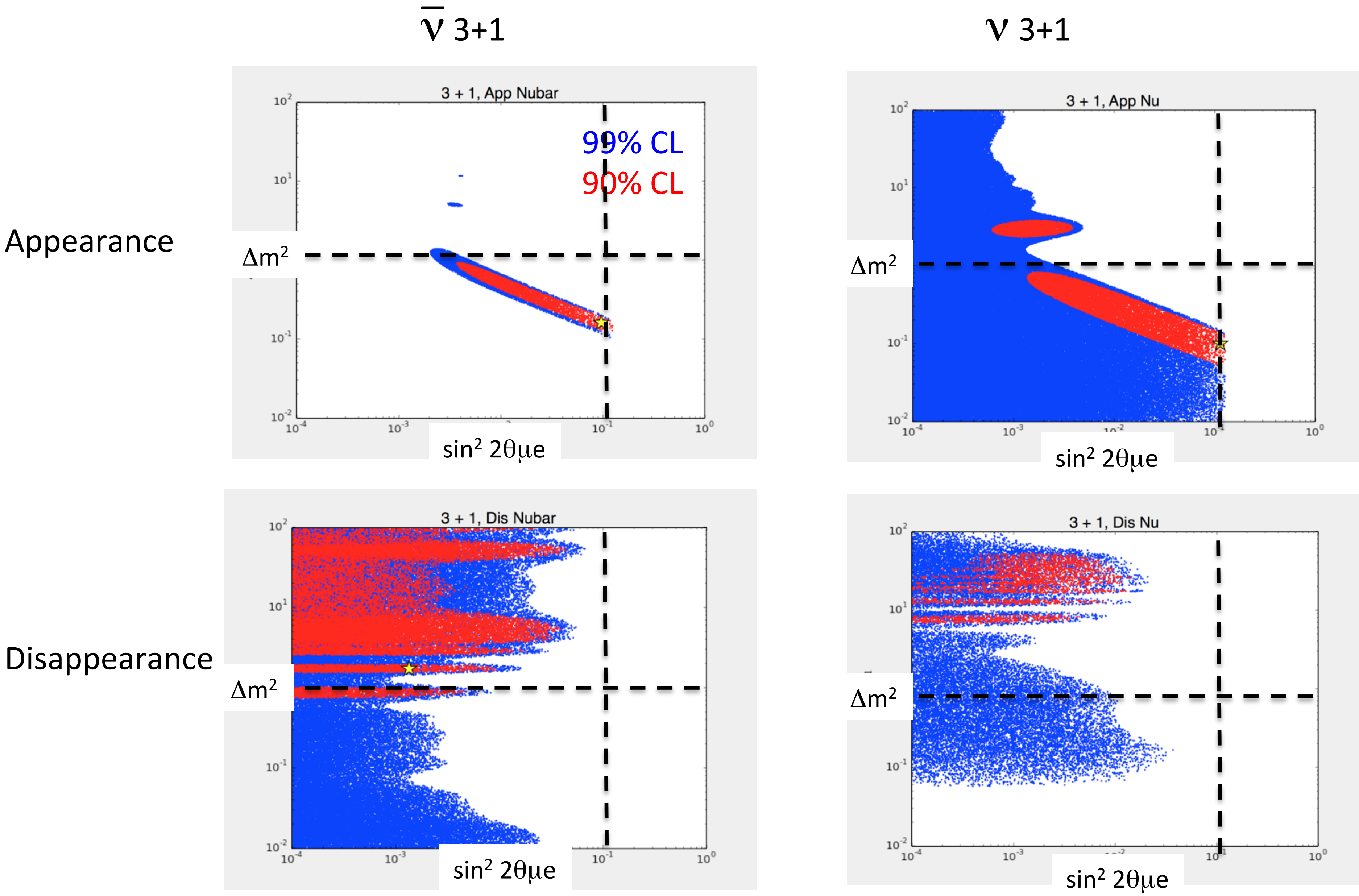
Fits by G. Collin, et al

2. What if we find there are issues with some of the observed signals, but not others, leading to the wrong global fit results?

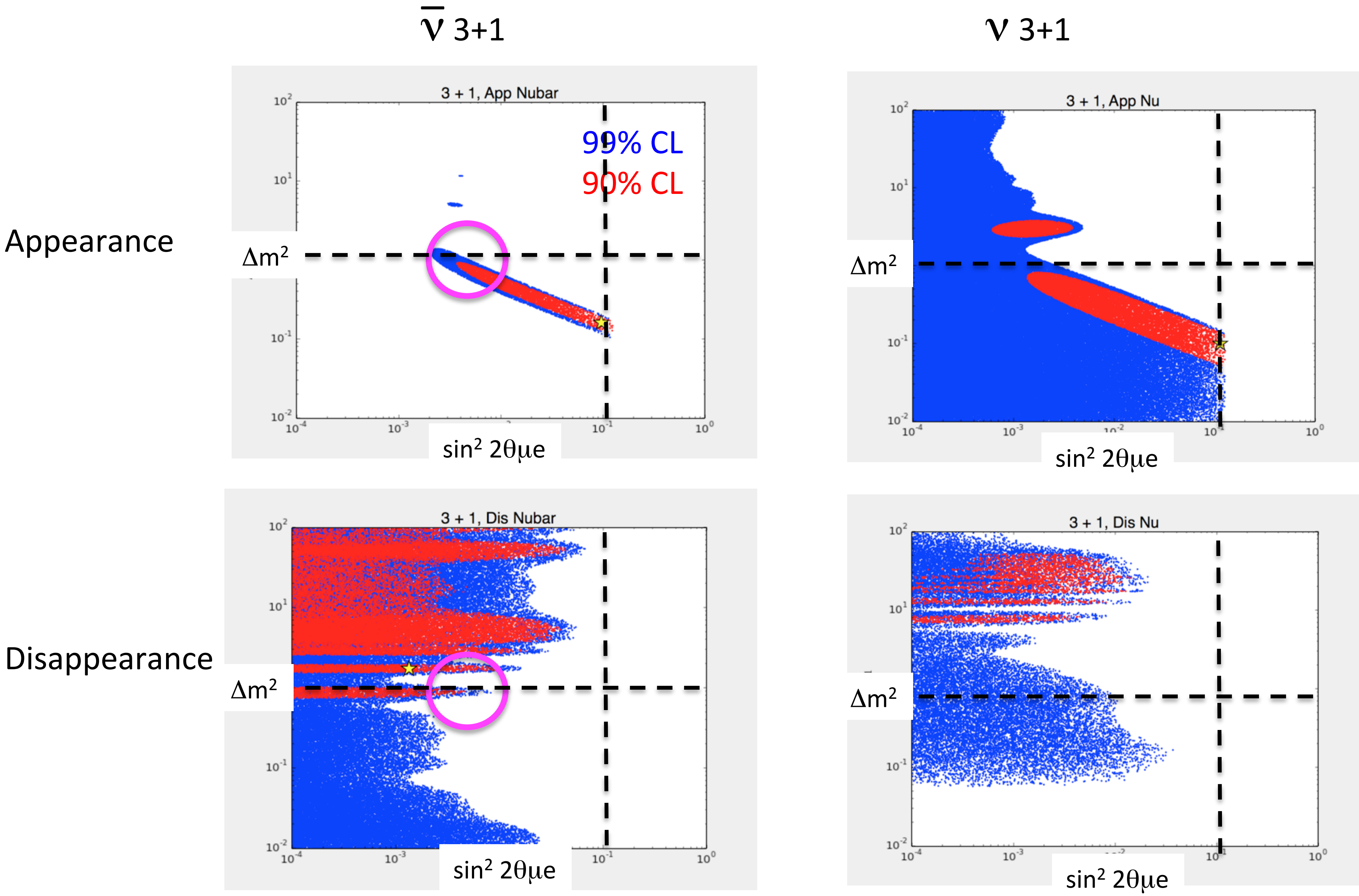
Why suggest this?

Let's divide the all of the data into two separate sets… $\bar{\nu}$ and ν,

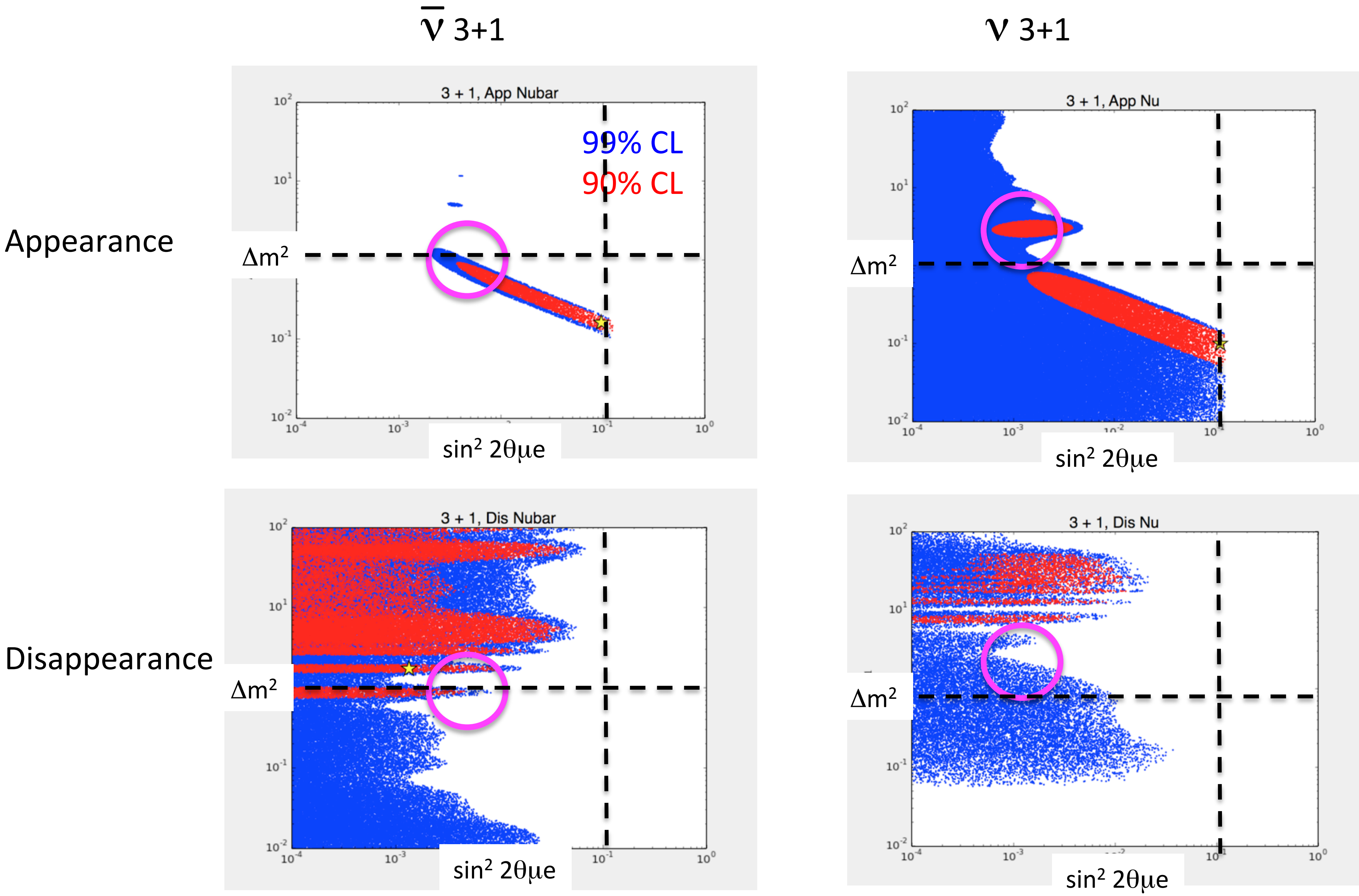
For each of these, let's do a 3+1 fit and look at the result
(This is very close to a 3+2 fit and it is easy to visualize)



Fits by G. Collin, et al



Fits by G. Collin, et al



Fits by G. Collin, et al

All 3 types of searches in BOTH running modes need to be rechecked!

Even with only subsets being right,
You are going to need a signal in ν_μ disappearance to make a sensible model!

It makes sense to proceed with new ν_μ disappearance searches now,
even in this scenario.

3. What if the tension has to do with background, not signal, and ν_μ disappearance is right around the corner?

In this case it is obvious we should proceed with ν_μ disappearance experiments, but why would I even bring this question up?

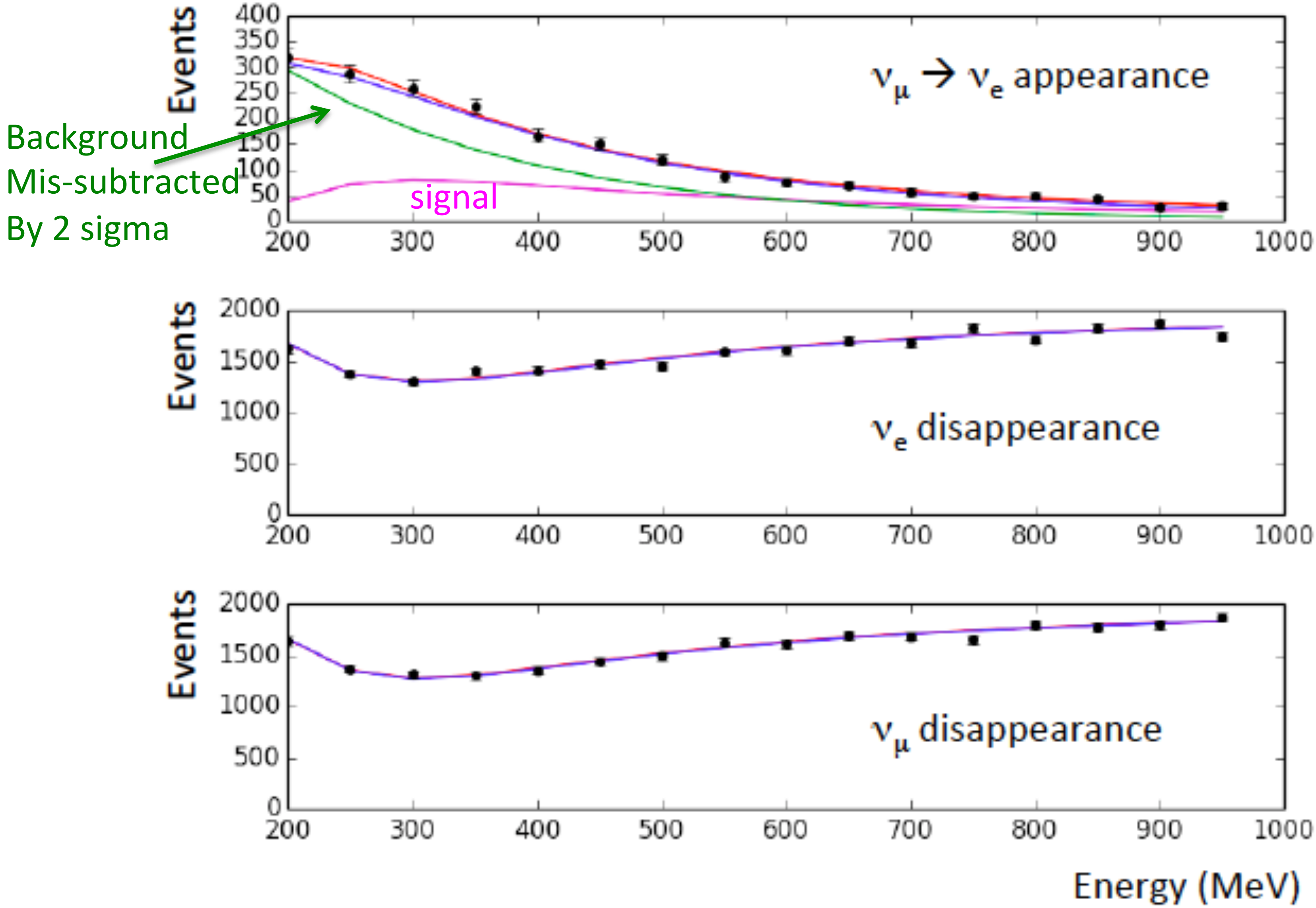
The PG test has a very specific flaw that can demonstrated with a toy model.

In the case where…

- You have an underlying systematic effect that is not Gaussian,
  (like a background that is mis-subtracted)
- And the associated shape correlates with a signal somewhere in parameter space,
- The test will return tension, even though the global fit is correct.

→ This is true even when the mis-subtraction is small when measured in "sigmas"

Consider this model



GH Collin, JMC, MH Shaevitz

What the PG Test evaluates:

$$\chi^2_{PG} = \chi^2_{glob} - (\chi^2_{app} + \chi^2_{dis})$$

Because of the correlation between the shape of the mis-subtracted background and the signal, this fit goes very wrong.

The result is that random experiments find substantial "tension" but in fact the global fit is returning exactly the toy model parameters.

We are in a situation where the global χ^2 is good.
but the PG returns tension.
We may be in the same situation as this toy model…
ν_μ disappearance may be right around the corner!

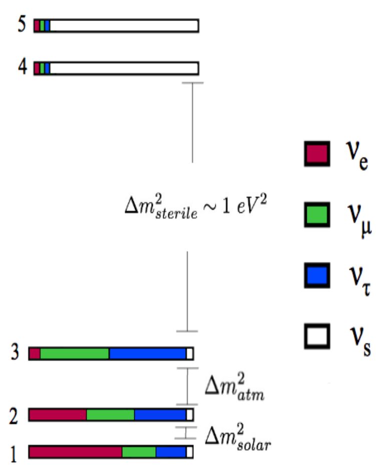
	χ^2_{best}	Pr
Null	290	1.5%
3+1	240	43%
3+2	235	45%

4. What if Nature is more complex than we thought?

A 3+1 model is clearly ridiculously naïve.
We should NOT be using 3+1 models as tests.
They are very misleading as to the capability of an experiment.

But just how complex is nature?
Is it a 3+2 model? This has a lot of obviously strange assumptions too…
The only parameters are…

$$\Delta m^2_{41}, \Delta m^2_{51}, |U_{e4}|, |U_{\mu 4}|, |U_{e5}|, |U_{\mu 5}|, \Phi_{45}$$



We are missing the other Δm^2s and
The light neutrino CP violating term!

And 3+3, as complex as those fits are,
we are also missing a lot of terms!

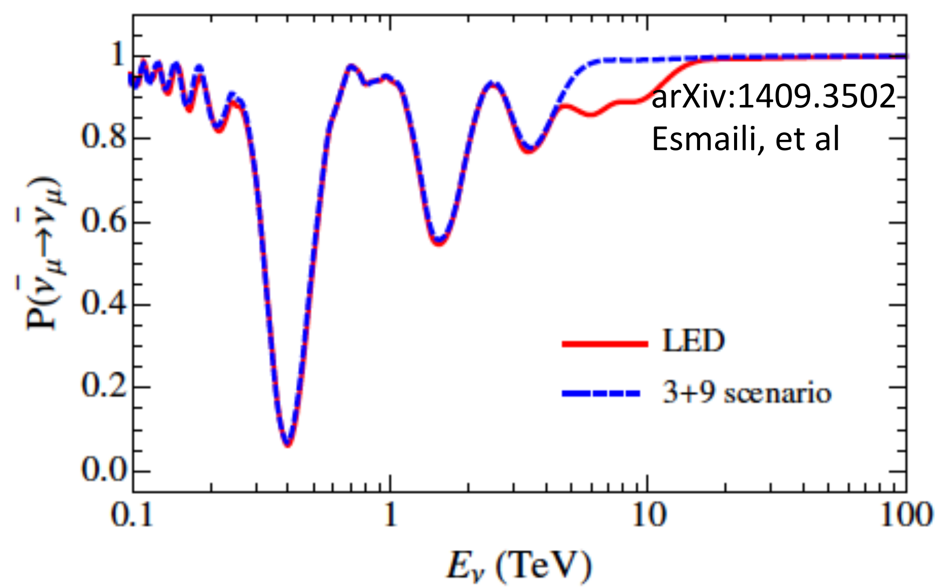
But maybe Nature is even more complex!

What if sterile neutrinos can also decay?
100% decay is ruled out as a model, But 3+N + decay is definitely not ruled out!

What if there are non-standard interactions affecting all of our measurements?

What if there is CPT Violation?

What if there are large extra dimensions? →



What if…
What if…
What if..

Your favorite theory extension here!

We really need ν_μ disappearance experiments where we <u>reconstruct</u> <u>the</u> <u>oscillation</u> <u>wave</u>!

It also says we need better modeling tools…

SQuIDS/nu-SQuIDS

C.A. Argüelles Delgado et al. [arXiv:**1412.3832**]

What is it?

Is a software framework written in C++ that **evolves quantum mechanical ensembles**.
nu-SQuIDS **calculates neutrino propagation** (oscillation+interactions).

What can it do?

- Calculate neutrino oscillation probabilities in 3 generations (can configure mixing angles, CP phases, and mass splittings).
- Ready to use in: short baseline, long baseline, atmospheric, and solar neutrino oscillation experiments.
- Incorporates neutrinos' non-coherent interactions (includes tau regeneration).
- Can handle collective neutrino interactions (e.g. super nova), as well as neutrino-antineutrino interactions.
- Easily extendable to BSM physics scenarios. **Sterile neutrinos,** NSI, and LV already implemented!

Get it here:

https://github.com/jsalvado/SQuIDS

https://github.com/arguelles/nuSQuIDS

Please Support Neutrino Phenomenology!

!

1. What if all of the existing anomalies are Standard Model?

2. What if we find there are issues with some of the observed signals, but not others, leading to the wrong global fit results?

3. What if the tension has to do with background, not signal, and ν_μ disappearance is right around the corner?

4. What if Nature is more complex than we thought?

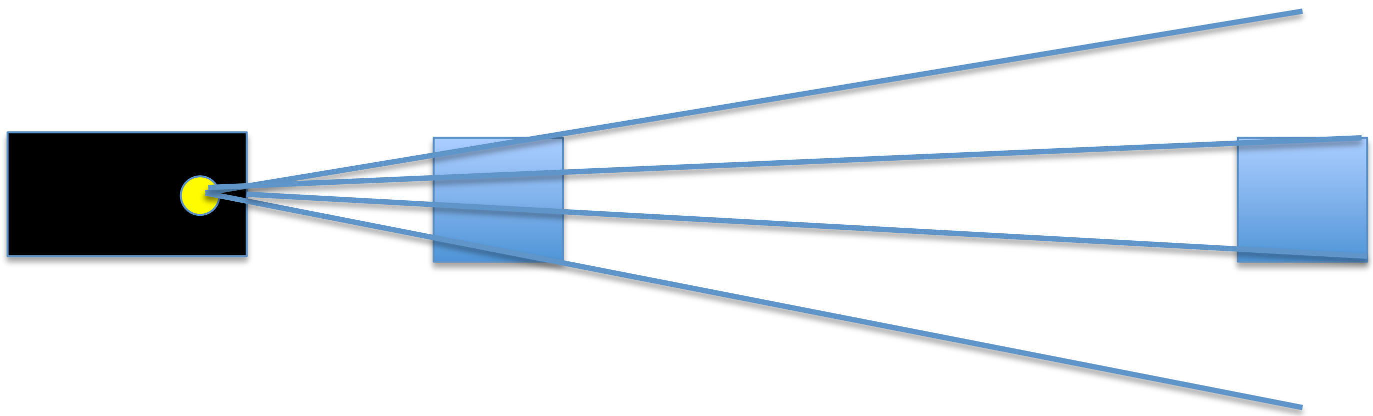
The Bottom Line for This Case:

All 4 of these scenarios point to the need for
much higher precision ν_μ disappearance experiments
in neutrino and antineutrino mode
in the near future

ν_μ Disappearance Experiments Need Well-understood ν_μ Fluxes

Decay-in-flight fluxes are difficult to simulate very well.

So most ν_μ disappearance experiments use near-far ratios.

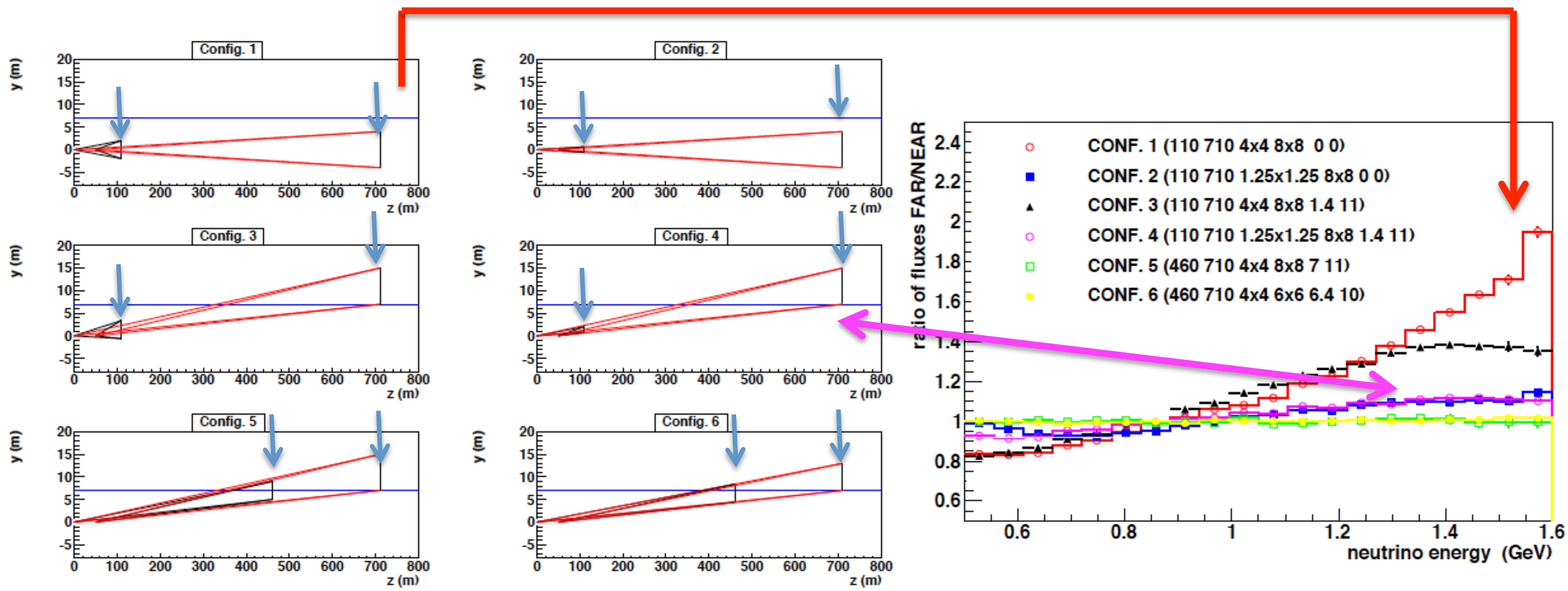


With CC interactions, you can reconstruct the neutrino direction,
And select only those events in the near detector that project to the far detector.

A study of configurations for the BNB (FNAL) beam by the NESSiE Collaboration

hep-ex/1404.2521

Flux ratios can show big differences
Between near and far detectors!

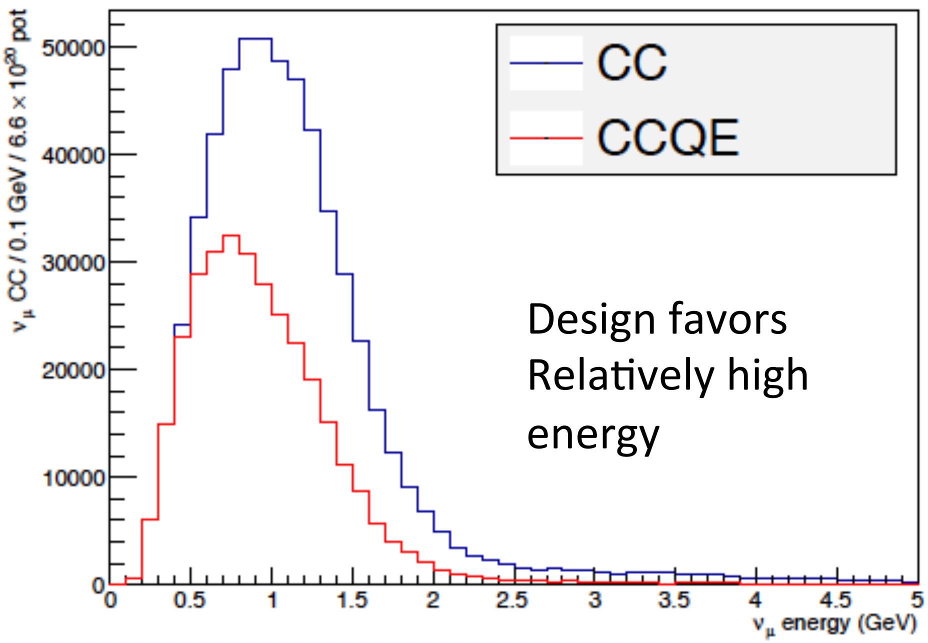


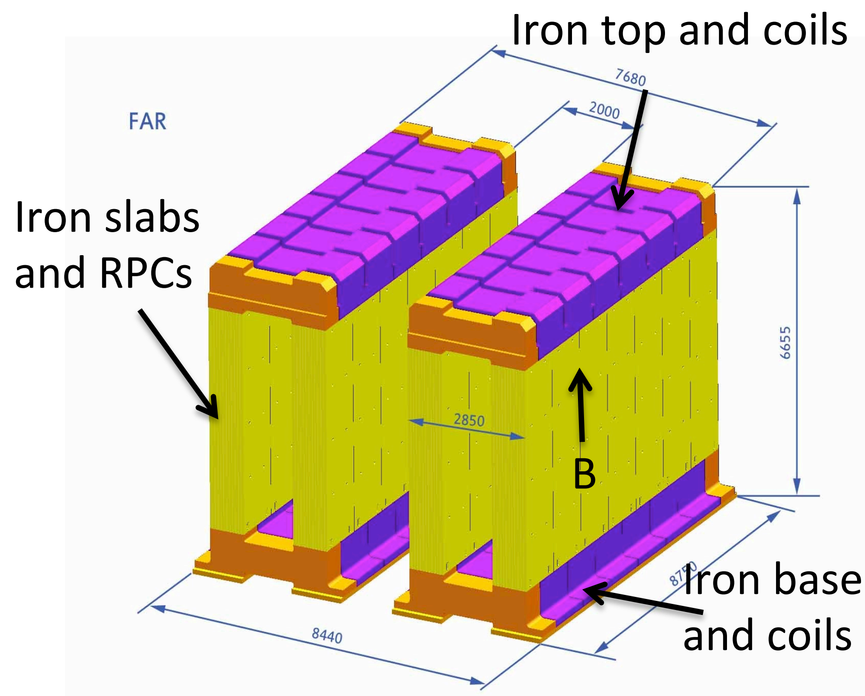
4 m x 4 m near 1.25 m x 1.25 m near
(Both designs have an 8 m x 8m far detector)

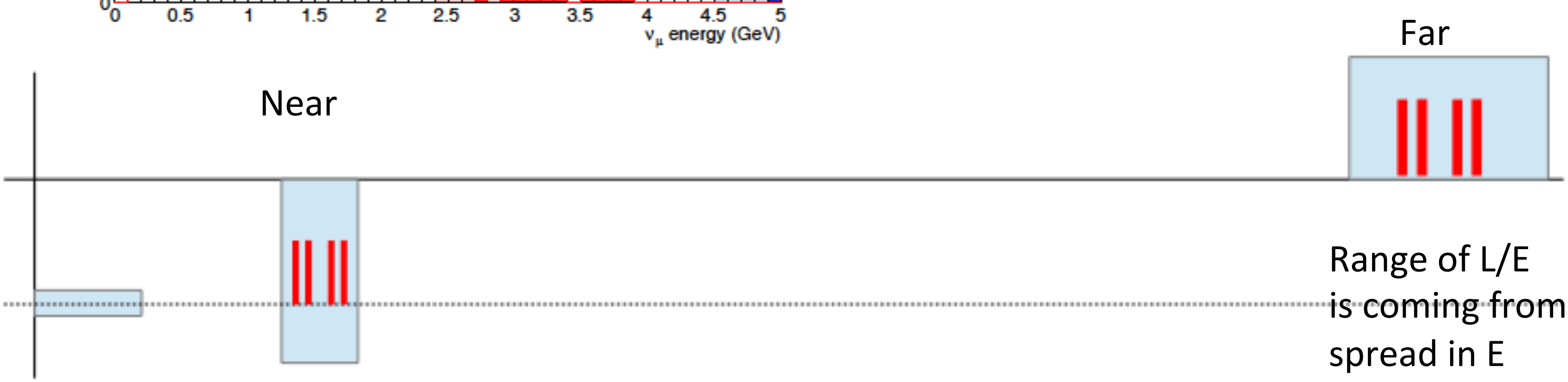
Choice is config. 4

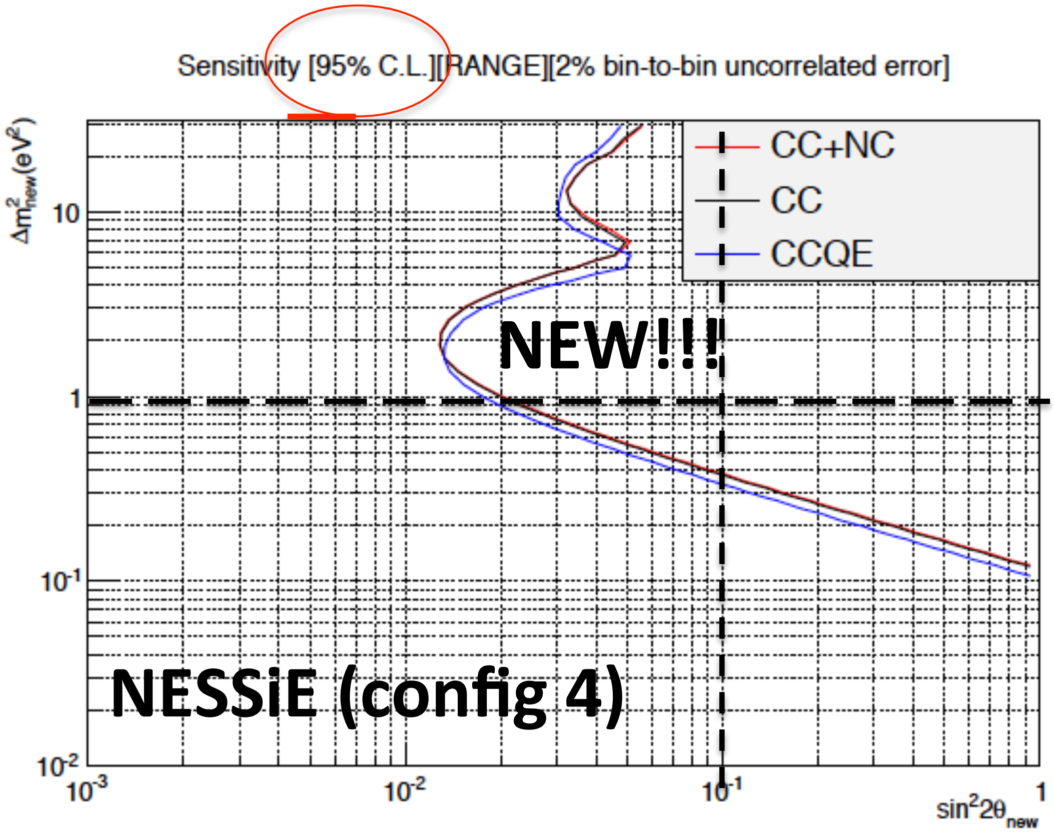
Need to understand the shape to ~1% level!

NESSiE is a magnetized detector,
With spectrometer design (and components!) drawn from OPERA

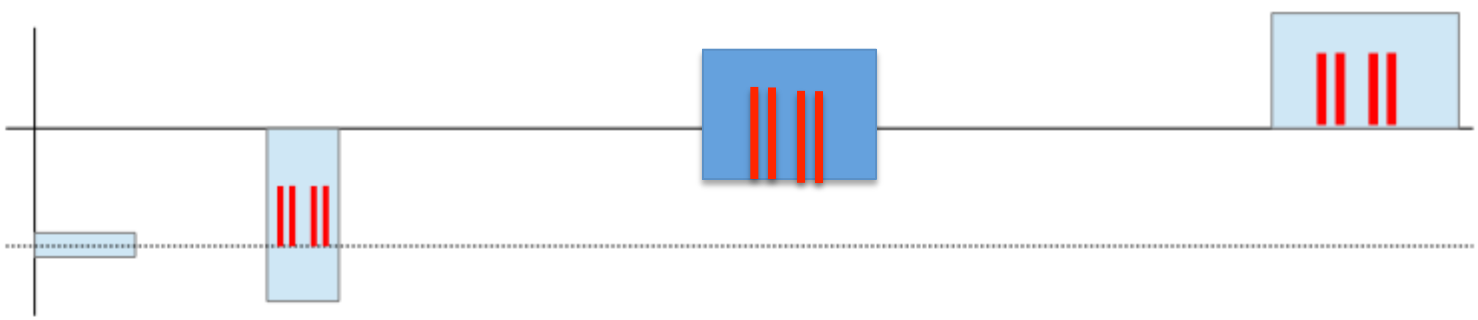








Really great sensitivity, but it will only be a single point measurement in L. What if this experiment had an intermediate detector too?

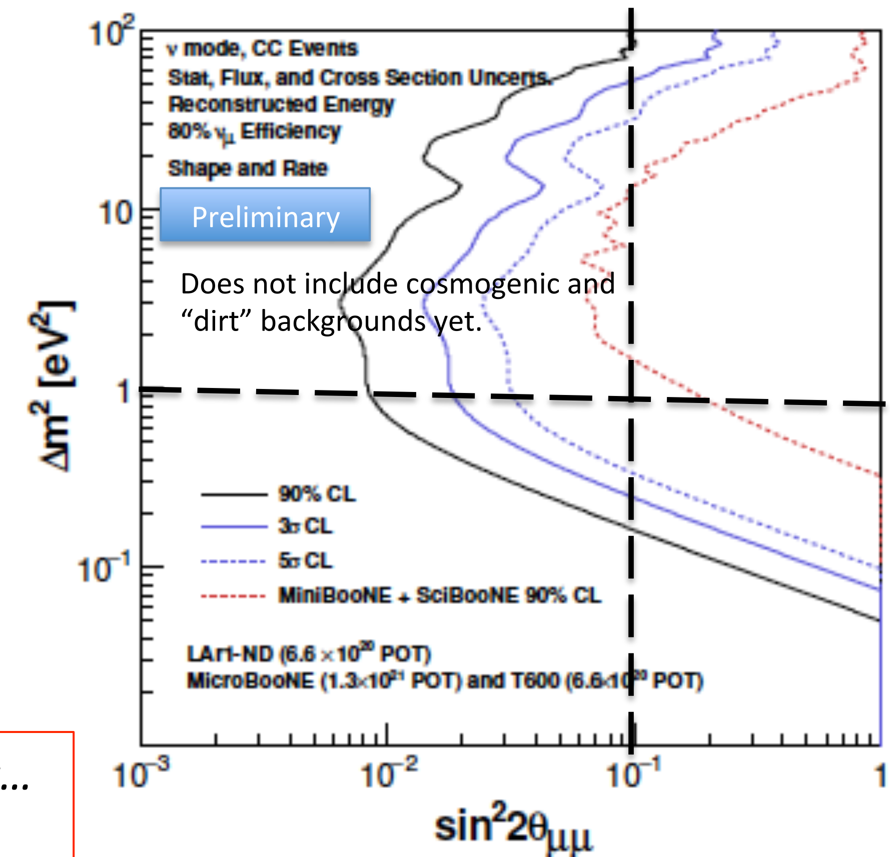


NESSiE is new to the plan....
Why not just rely on the "SBN" liquid argon detectors and forget other approaches?
After all, they will already be there for the ν_e appearance studies!

LAr technology is not optimized for muon reconstruction.

Exiting muon momentum is determined through multiple scattering.

Very soon MicroBooNE will give us a good sense of how well this can be done on the BNB line!



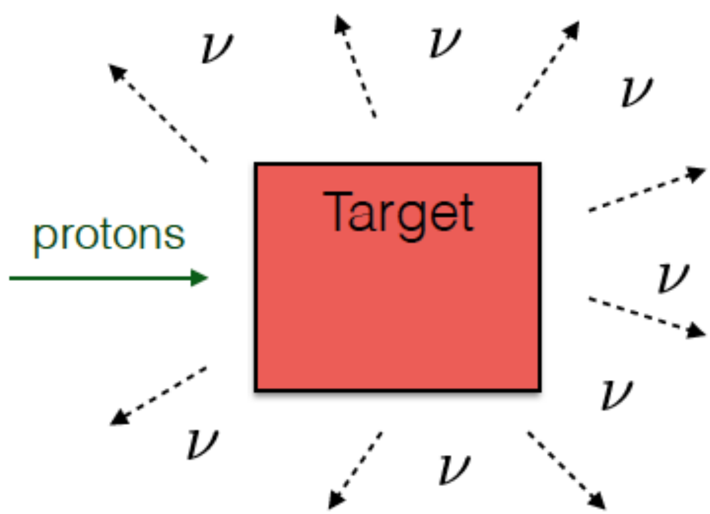
It is great we have SBN-LAr, but…

If we really want to understand ν_μ disappearance waves, then we probably need detectors that specialize in muons

!

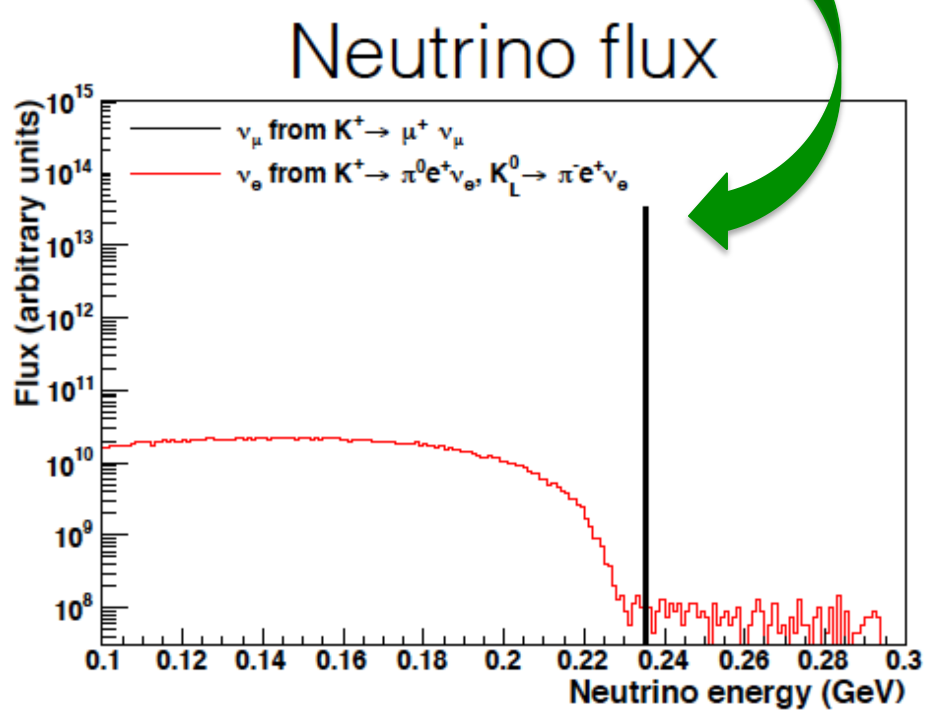
An idea that no one has looked at yet for ν_μ disappearance:
Can we use KDAR?

J. Spitz, Phys. Rev. D 85 093020 (2012)

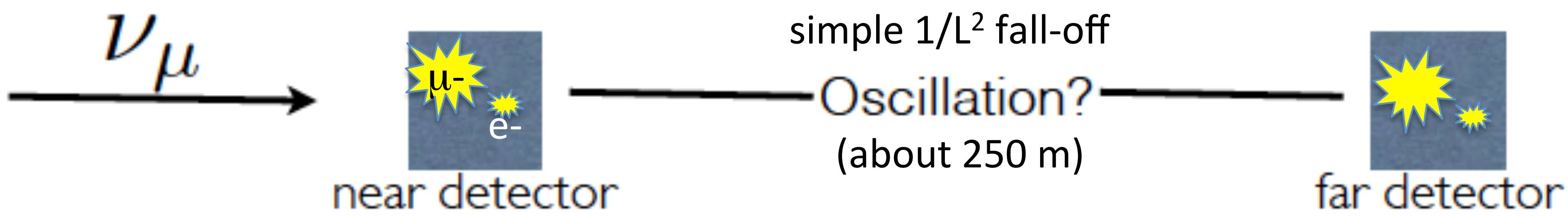


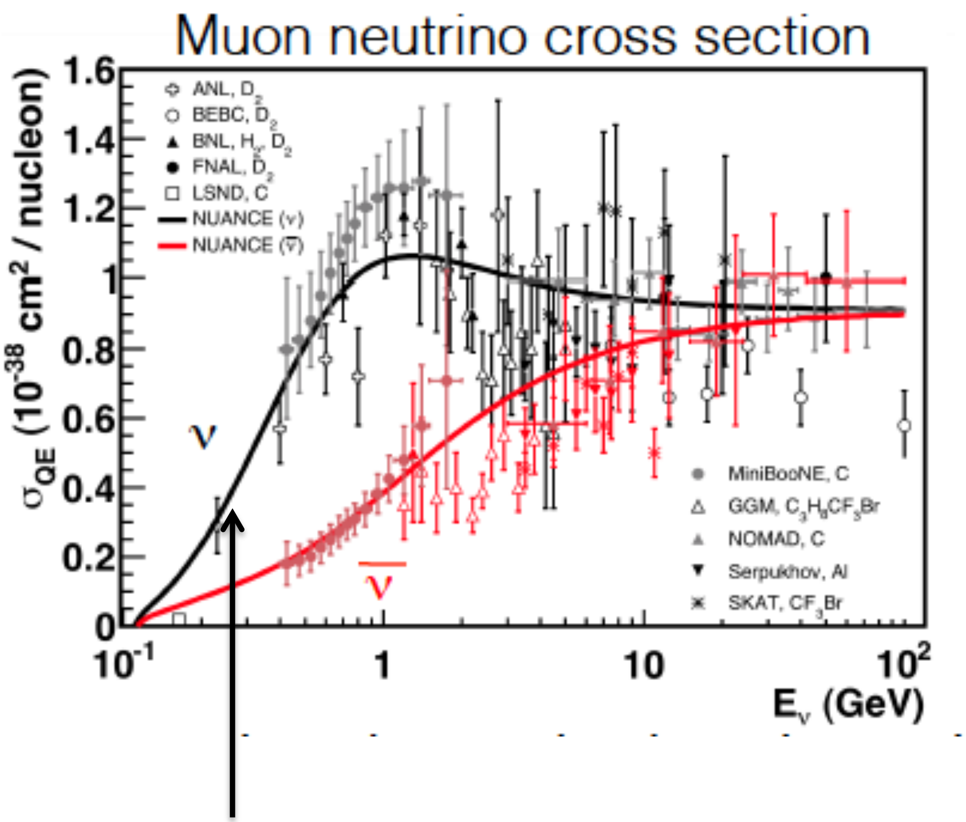
$$K^+ \to \mu^+ \nu_\mu$$
$$K^+ \to \pi^0 e^+ \nu_e$$
$$K_L^0 \to \pi^- e^+ \nu_e$$

Unlike the BNB line, this flux is mono-energetic and isotropic.



JPARC MLF is offering this beam NOW



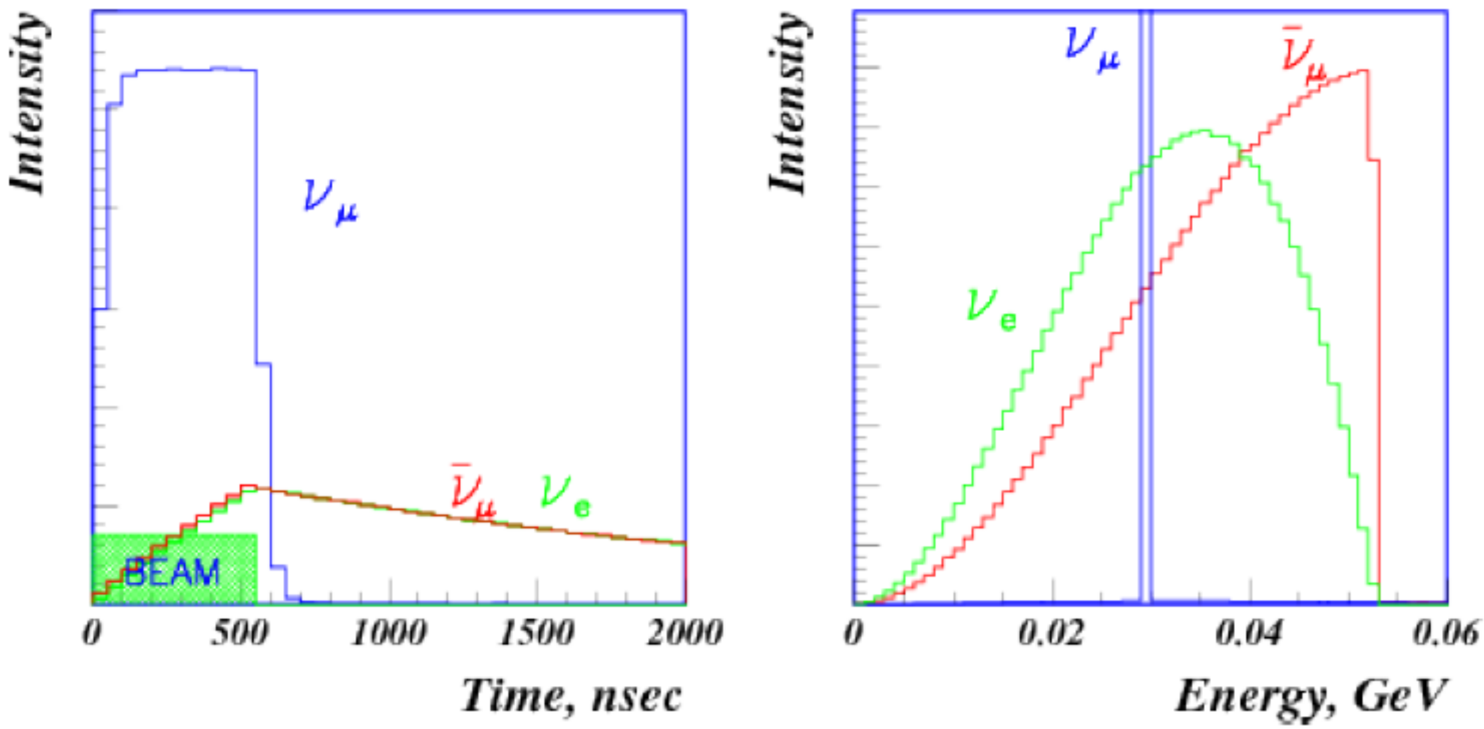


No sensitivity calculation yet,
but seems to be
a practical design
for tracing
the osc wave.

Just put lots of little 50 ton
liquid scintillator
detectors in line…
<u><$10M, fast, & Beam exists!</u>

Despite low xsec @ JPARC MLF -
1000 ν_μ CC events at 250 m with 50 ton detector in 4 years

π/μ DAR also has a monoenergetic ν_μ flux,
And, given a bunched beam structure, it is prompt!



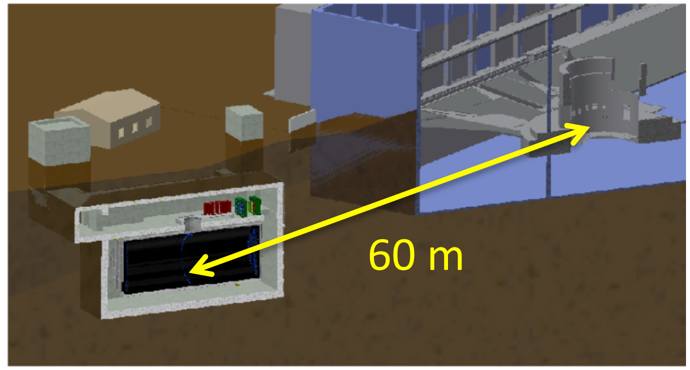
Too low energy for CC scattering,

OscSNS Concept, use NC:

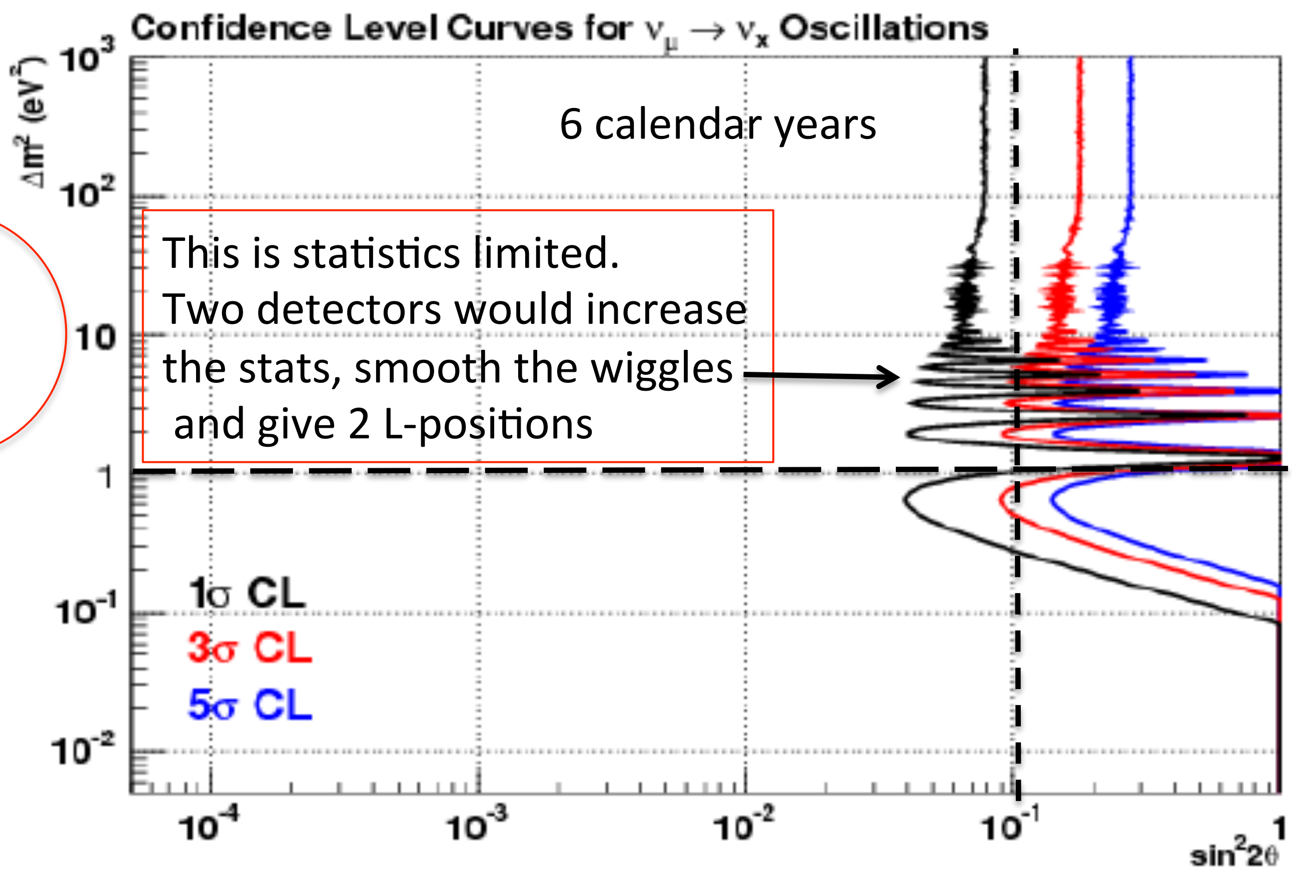
$$\nu_\mu \ {}^{12}C \rightarrow \nu_\mu \ {}^{12}C^*$$

hep-ex/1305.4189

OscSNS is 800 tons
Of lightly doped LS



1.4 MW
source



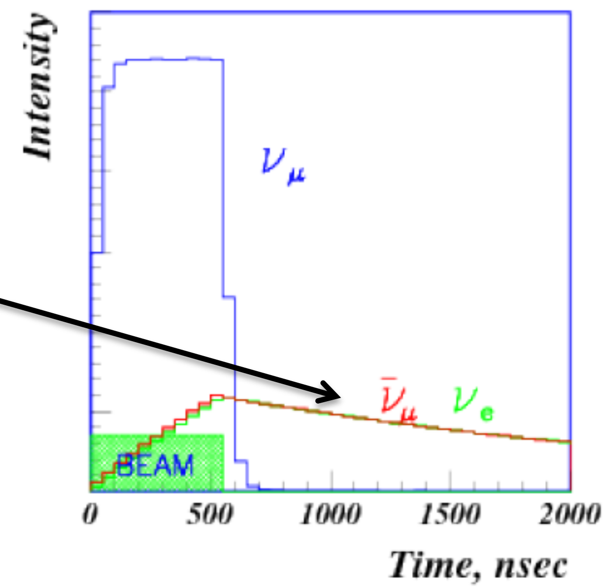
$\bar{\nu}_\mu$ Disappearance Studies Suffer from a Lack of Pure Beams

Where can we find high rate, high purity muon antineutrino fluxes?

π/K decay in flight (eg BNB) → Very low rates. Poor purity. No present plans!

What about DAR? Can OscSNS do it?
→ μDAR mixes
ν_e and $\bar{\nu}_\mu$ disappearance signals
in NC mode

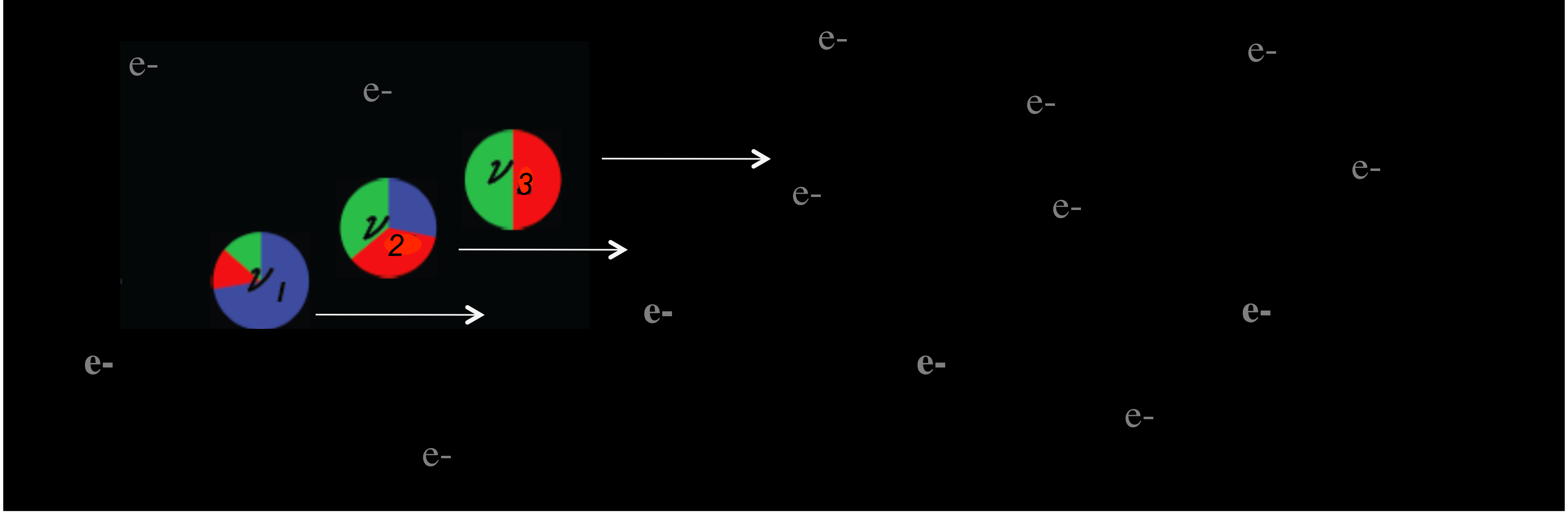
Atmospheric? Also a $\nu/\bar{\nu}$ mix!



It looks really hard
to find $\bar{\nu}_\mu$ flux purity...

Thinking a little outside the box on this problem....

"Matter Effects"



- Electrons in the earth produce a "weak-interaction potential"
- Effect is opposite sign for neutrinos and antineutrinos

At <u>high energies</u> and <u>long distances</u>, oslashillations will be affected.
→ You get BIG disappearance effects <u>in only one mode</u> (ν or $\bar{\nu}$),
which mode depends on the hierarchy

Pick 2 -- Get the 3rd

With 3ν, we know these two

→ Use these to find the hierarchy

Know your neutrino and antineutrino content

Know your oscillation parameters

Know your Hierarchy

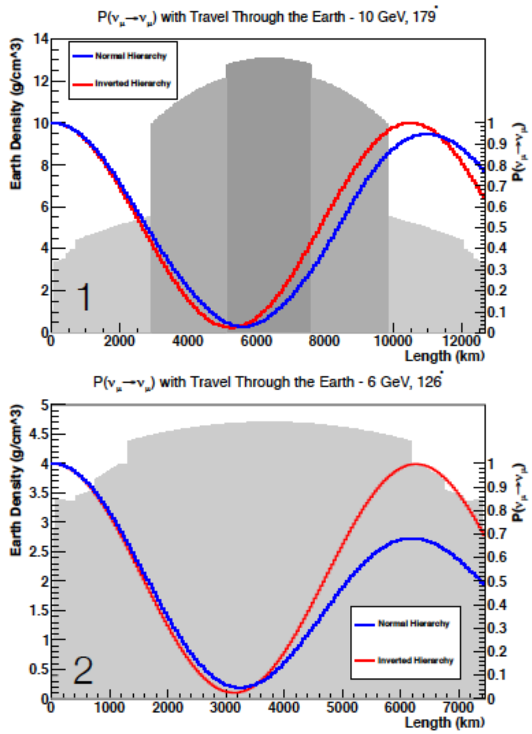
In the case of sterile neutrinos, we think we know these two

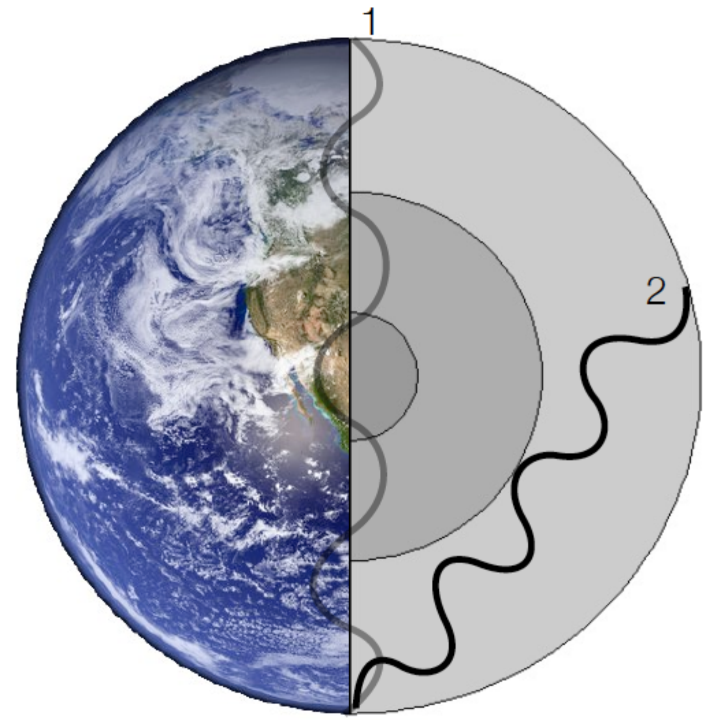
→ Use these to find the osc. parameters

Let’s use IceCube/PINGU as our example…

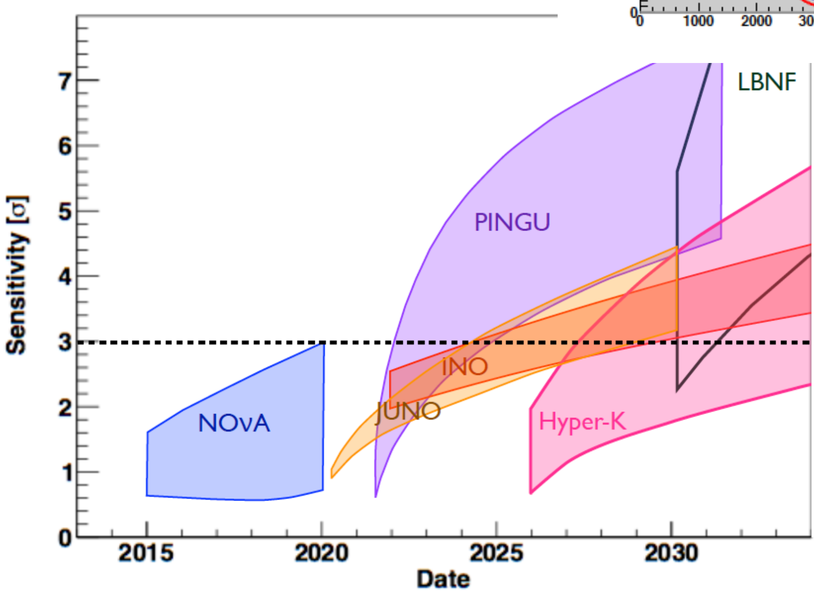
This is how PINGU works for 3-Neutrino Hierarchy Studies…

Because the oscillation parameters are known, the waves through the paths are predictable





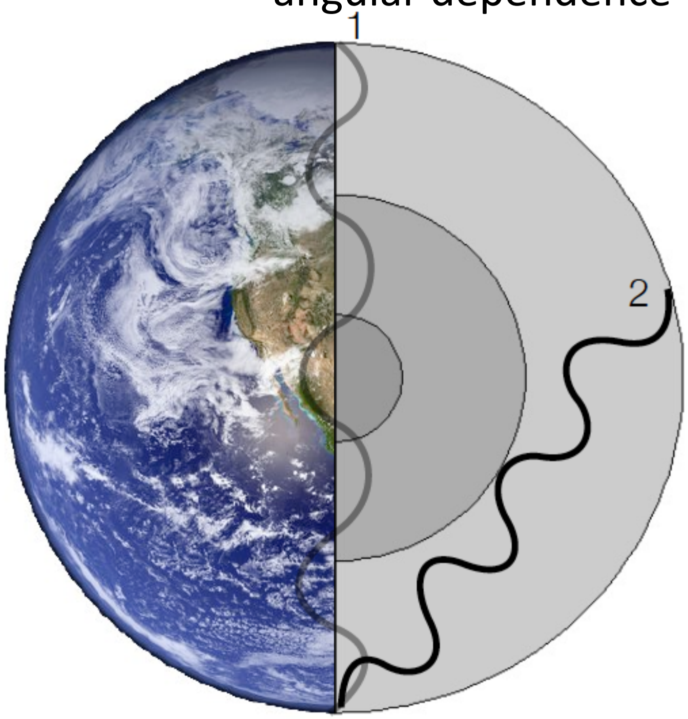
Graphic from J. Koskinen



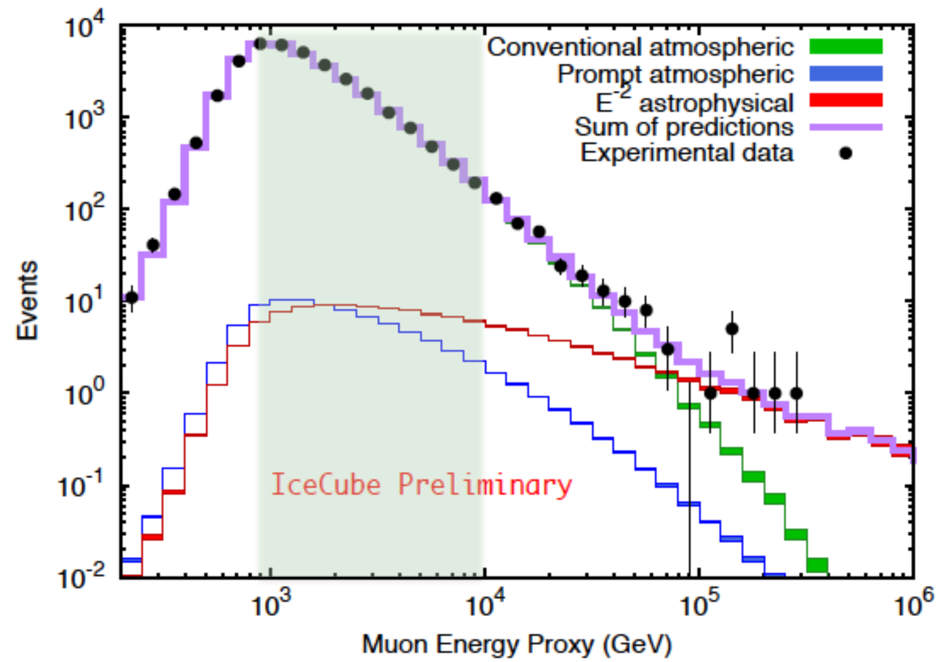
The result is very powerful sensitivity to the hierarchy!

Using the exact same trick for sterile neutrinos, knowing the hierarchy, not the osc parameters…

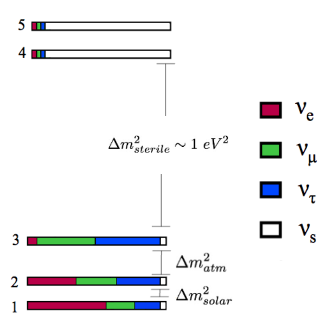
Use the angular dependence



Neutrinos in the 1 to 10 TeV range (optimal for sterile neutrino matter effects In the earth)



Use the Hierarchy:

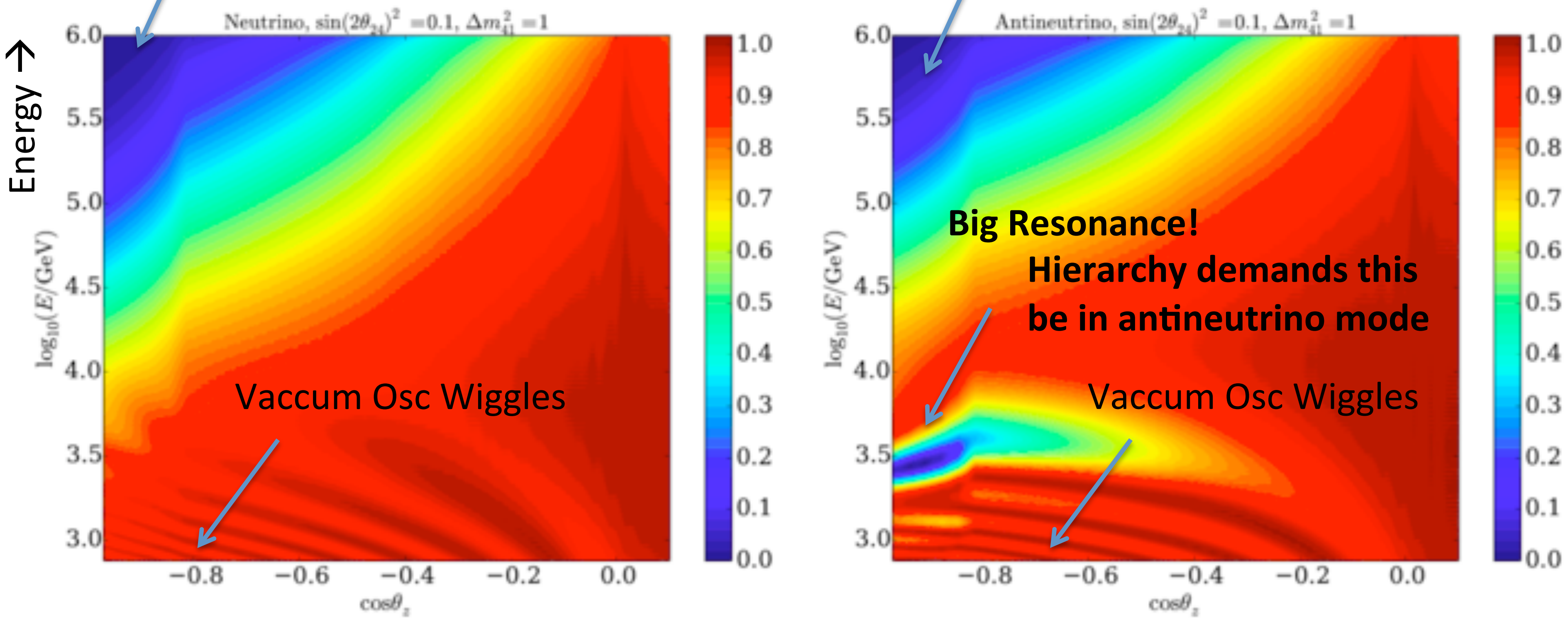


This is where IceCube has enormous statistics!

From NuSquids,
(*Argüelles Delgado, et al*)

Oscillograms 101

Neutrino Absorption (at TeV energies, neutrinos are absorbed by the earth)



Up (through core) Horizon Up (through core) Horizon

Matter Signal antineutrino, because of the known hierarchy
→ Access to the antineutrino ν_μ oscillation parameters!

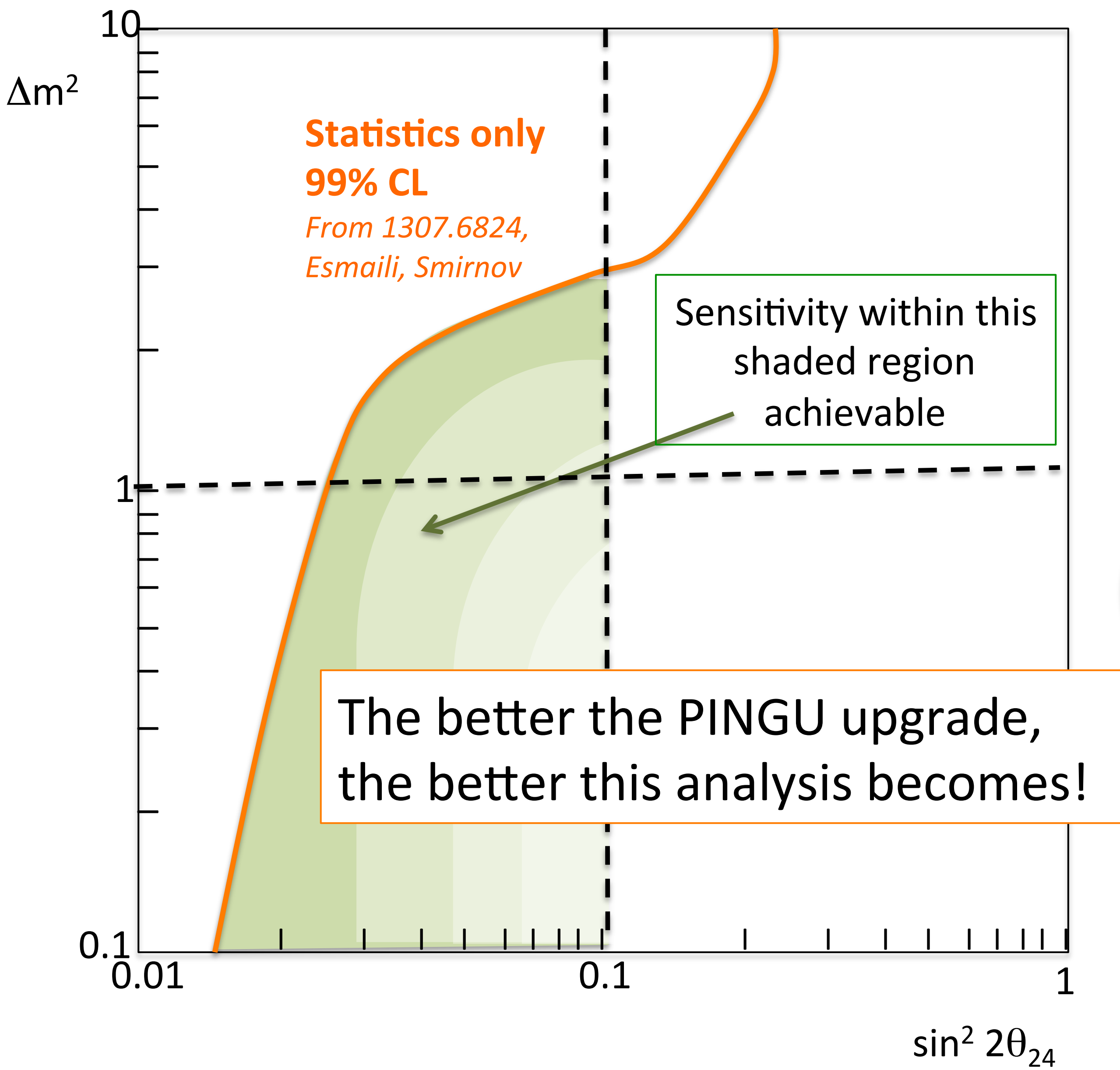
Three ways this signal is special

1. Wow, that signal is BIG!

2. That signal assumes our QM model of oscillations,
   so this tells us a lot about our sterile model!
   (& would be the first MSW resonance observed!)

3. Any measurement of the osc parameters extracted,
   will be the first measurements in muon <u>antineutrino</u> mode!

Potentially powerful!



First results are already on their way!

(Marginalize over other parameters)

More Ideas
can be
Brought
to the Table!

What about ν_τ appearance?
→ observable in IceCube/GenTwo, how else?

What about NC disappearance, even with more complex beams?

→ e.g. coherent scattering experiments at π/μ DAR sources (maybe ultra-high stats & ν_e disappearance data can allow $\bar{\nu}_\mu$ signal to be separated from ν_e ...?)

Conclusion on ν_μ disappearance

- We <u>need</u> a strong ν_{μ} disappearance program.

- There is lots of room for your ideas and "new approaches"!
  Could be room for new <$10M experiments.

- This area of study is not necessarily technically limited.
  We can do a lot without a lot of R&D!

There is a lot of scientific potential in the sterile neutrino program!

Let’s discuss!